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V. An Investigation of the Spread of Fatigue within Narrow Frequency Limits

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Bureau of Medicine and Surgery, Navy Department,

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16 May 1952

THIS REPORT CONCERNS . . . . .

The ability of the ear to perceive tones of varying frequencies when these test tones follow initial presentation of a 1000 cps. tone.

IT IS FOR THE USE OF . . . . .

Those concerned with the psychoacoustics and human engineering aspects of repetitive pure tone stimulation, such as found in Flybar, radio code, submarine and anti-submarine sonar.

THE APPLICATION FOR THE SUBMARINE FORCE . . . . .

From these data one can calculate the total fatiguing effect over the frequency spectrum of a frequency approximately that used in sonar echo-ranging equipment. When the study is extended to other frequency regions, one should be able to calculate the total fatiguing effect of any stimulus however complex.

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A B S T R A C T

If a tone is sounded in one ear and immediately a second tone is sounded, there is a decrease in sensitivity to the second tone.

A 1000 cps. tone was presented to five observers for 435 msec. followed by a silent interval of 35 msec., then a test tone of 50 msec. was presented. The first tone was given at sensation levels of 30-90 db. in 10 db. steps. Frequencies of the second tone were varied randomly from 900-1100 cps. The greatest decrement in sensitivity was found for test tones from 990-1010 cps. in the form of a broad spread at the higher sensations levels. At the lower sensation levels only a slight effect was found.

STUDIES IN SHORT DURATION AUDITORY FATIGUE

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INTRODUCTION

The classic picture of the basilar membrane as a system of resonators has led to the view of this membrane as underlying an organism's frequency selectivity. According to this view, the frequency discrimination of an organism gives a cue to the sharpness of tuning of the resonating elements. Actual discrimination, however, has always predicted a sharpness of tuning which did not seem reasonable in view of what was thought to be the almost critical damping of the ear.

Modern auditory theory does not allow for resonance of the basilar membrane in any sense except that of a rough analogue, but the problem of the sharpness of "tuning" in the peripheral organ remains to be solved. Whether this "tuning" is a function of the basilar membrane, or the tectorial membrane, or of the hydrodynamics of the cochlea, is not important for the argument. It is known, at least, that the maximum amplitude of motion of the basilar membrane (and indeed of the whole cochlear duct including Reissner's membrane) is a function of frequency, and that the pattern of vibration is also a function of frequency, being somewhat more sharply peaked at high frequencies than at low (1, 2). These broad patterns do not seem able of themselves to subserve the fine frequency discriminations commonly reported.

On the other hand, a broadly-peaked amplitude factor does not exhaust the organism's powers of frequency analysis. Huggins (7) and Huggins and Licklider (8) have indicated other mechanisms able to be recruited for the job.

One line of inquiry into the facts of frequency selectivity has been

by way of the masking experiment. By making one or two assumptions, masking curves showing the effect of a pure tone on adjacent frequencies can be thought of as representing activity patterns along the basilar membrane.* This approach has been brought to its most advanced stage by Steinberg and Gardner (15), who calculate, for the masking frequency, the loudness in millisones per mel contributed by adjacent portions of the basilar membrane. But although the masking experiment has the virtue of being a functional test, and is in that sense superior to the observations of Bekesy, an insurmountable difficulty appears. What one wishes to know is whether within very narrow frequency ranges sharp or broad activity patterns occur. Yet it is just with these closely adjacent frequencies that auditory beats invalidate the experiment. An ingenious attempt has been made by Schafer, et al. (14), to overcome the objection by masking with narrow bands of noise, but the region of beats has still not been covered.

The technique of short-duration fatigue was used by Luscher and Zwislocki (9, 10, 11) and by Munson and Gardner (12) to work out the broad features of frequency selectivity from a functional standpoint. In this technique, a stimulating tone is given, then after a brief silence, a second tone is presented. Under these conditions fatigue refers to the loss of sensitivity to the second tone. Since all durations and intervals are fixed at much less than one second, fatigue occasioned by the first tone is slight and evanescent, and an absolute threshold for the second tone can be found quickly. The technique has two advantages over the masking experiment for the purpose of studying activity patterns. First, the two tones can be separated by only a cycle per second, or less, without the presence of beats, and second, no complication results from the intrusion of inhibition, summation, or other neural interaction present in simultaneous stimulation.

Previous authors have not used short-duration fatigue in the region of beats, where the data would seem to be of especial importance in the theory of frequency discrimination. The present experiment used the technique to cover the region of beats with particular care.

* These assumptions are that masking is a function of loudness, and that the mel scale can be related to linear distance along the basilar membrane.

APPARATUS AND PROCEDURE

The outputs of two oscillators* were led through an amplifier with rise and decay times of 25 milliseconds, then through a power amplifier, attenuation circuit, and finally to a Permoflux PDR-8 earphone in a supra-aural cushion. A wooden replica earphone filled the cushion on the other side of the headband. An electronic switch controlled all time intervals.

A stimulating tone was passed for 435 msec., followed after a 35 msec. silent interval by the test tone, 50 msec. in duration. The intensity of the 1000 cps. stimulating tone varied from 30 through 90 db. sensation level.

The test tone was varied in 2-cycle steps from 990 through 1010 cps. Subsequently the frequency range was widened to include test tones of 900, 950, 960, 970, 980, 1020, 1030, 1040, 1050, and 1100.

At the beginning of each experimental session, the oscillator producing the first tone was set at the desired frequency by coupling it to a Hewlett-Packard low frequency standard, and the frequency of the second tone was quickly equated to the first by beating them on an oscilloscope. The S at this point put on his headband and adjusted it for comfort. Then, without further adjustment of the headband, three thresholds were obtained in the following order: (a) for the first tone alone, by the serial method of limits (two ascending and two descending series); (b) for the second tone alone, by the method of constant stimuli (five or in some cases ten judgments at intensity levels in 2.0 db. steps at random until 100 per cent and zero per cent positive responses occurred); and (c) for the second tone preceded by the first tone, by the method of constant stimuli exactly as for (b). The difference between thresholds (b) and (c) was used as the measure of fatigue.

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* A Hewlett-Packard Low Frequency Standard, set at 1000 cps, produced the first, or stimulating tone; a General Radio Interpolation Oscillator, continuously variable in frequency, produced the second, or test tone.

In determining threshold (c), the fatigued threshold, subject (S) was first given several sequences of both tones in the temporal pattern described above, with the second tone well above, and then well below, his threshold. This allowed him to stabilize his criterion of whether he heard a second tone. As the experimental sessions continued, this practice was reduced to two sequences per session or whenever S called for it. The S was required to respond positively or negatively to every sequence except those used for practice. In cases of uncertainty, no data were recorded and the sequence was repeated.

After the fatigued threshold had been determined, S was allowed to remove his headband and rest until he again felt prepared to undergo another session, whereupon the oscillator producing the second tone was set to a new frequency and the entire three-threshold procedure was repeated.

Five determinations of fatigue were made at each frequency for each of a selection of sensation levels from 30 through 90 db.

Finally, for each S individually, the mean threshold, its standard deviation and standard error, were calculated for each experimental condition.

RESULTS AND DISCUSSION

Although average data from the five observers (Os) reflect fairly accurately the effect of frequency differences, nevertheless the usual wide variation in susceptibility to fatigue appears. It seemed best first to present typical data from two Os. Figures 1 and 2 show two individual fatigue curves as a function of frequency of test tone; parameter is sensation level of fatiguing tone. Figure 3 shows the mean data for all five Os.

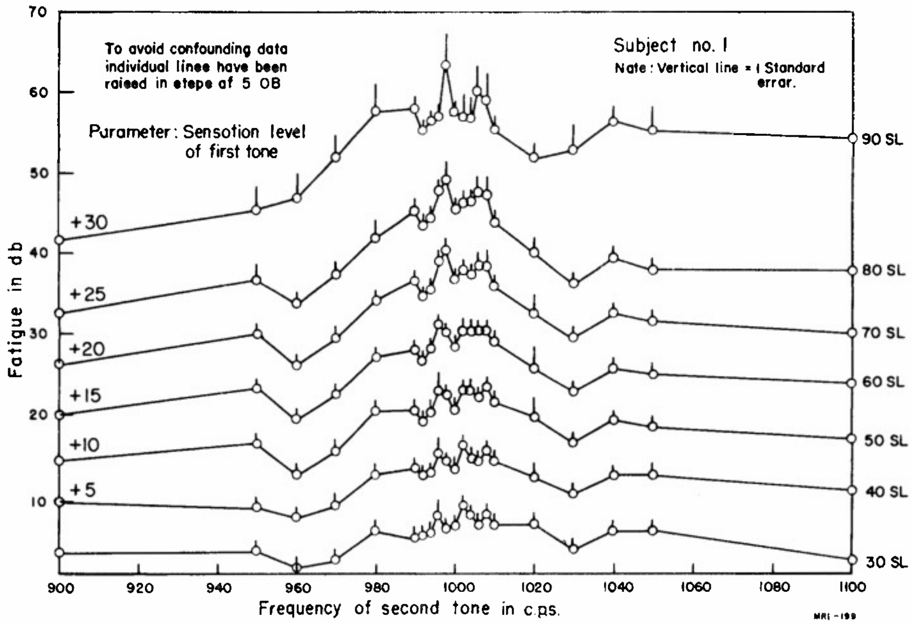

Figure 1. - Tuning of the Basilar Membrane at 1,000 cps for Subject No. 1

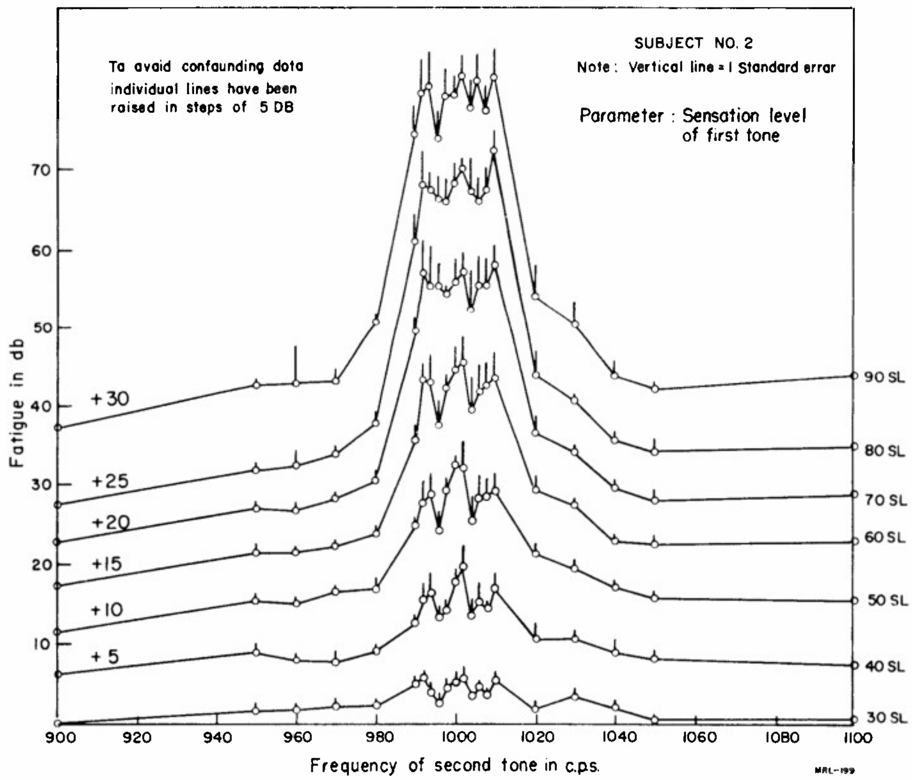

Figure 2. - Tuning of the Basilar Membrane at 1,000 cps for Subject No. 2

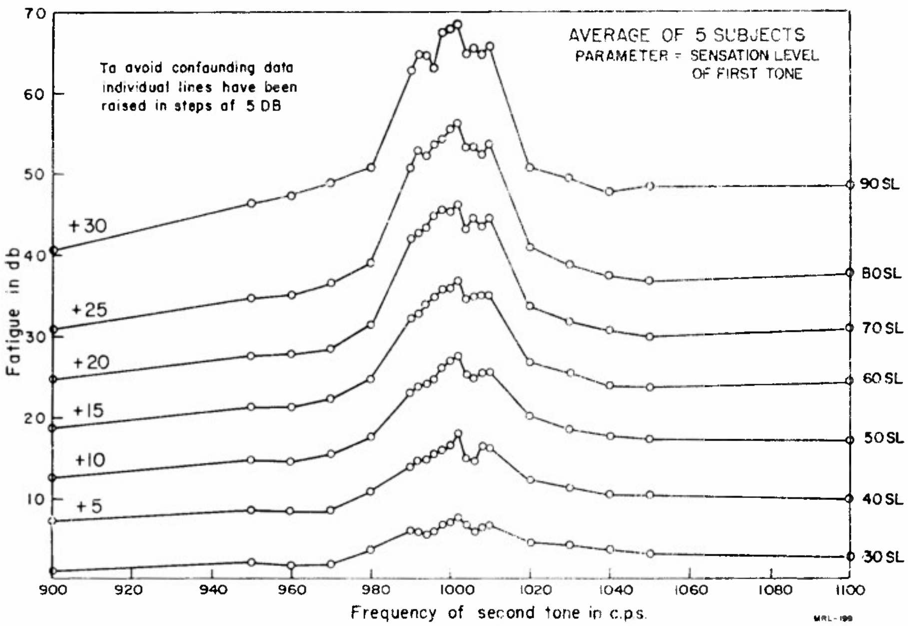

Figure 3. - Tuning of the Basilar Membrane at 1,000 cps - Average of Five Subjects

With regard to the main question as to the "tuning" of the cochlea, the spread of fatigue from 990 through 1010 cps. is uniformly broad at all intensities of stimulation and for all Os. This lack of any sharp distinction through a range of at least 20 cps. is in marked contrast to what would be expected from the facts of frequency discrimination. Indeed, it is only at the higher sensation levels where any peaking at all appears even within the 20 cps. spread. The picture, at low intensities, is of a very slight influence at adjacent frequencies through even a 200 cps range.

The facts seem to be the reverse of what one would expect from what is known of the spread of excitation with increased intensity. In the simultaneous masking experiment, for instance, the weakest masking tone exerts an influence only on rather closely adjacent frequencies, the range of masked frequencies broadening as the masking tone increases in energy. Something of the same general nature appears in figures 1 and 2, of course, but there is no indication in the simultaneous masking experiment of an increased sharpness of tuning with increased energy of stimulus.

(When simultaneous masking data are cast into loudness patterns by means of a series of assumptions, as Fletcher and Munson (5) and Steinberg and Gardner (15) have done, an increased sharpness of tuning with increased energy input is seen; but the fundamental data of simultaneous masking do not reveal this condition, and casting the present data in such a form would only accentuate the distinct difference here found between weaker and more intense inputs.)

Pitch discrimination data were available on all Os at 1000 cps. for a wide selection of sensation levels. No tendency could be discerned for those with better discrimination to show sharper peaking of fatigue data. The range of pitch discrimination ability was, however, rather limited in this group. It might be mentioned, on the other hand, that in one O with a differential pitch threshold of about 1 cps. (Figure 1), the peaking was no sharper than in an O with threshold of about five cps. (Figure 2). It was true that the Os with better discrimination showed less fatigue under all conditions, but this relationship may have come about through the changes wrought in discriminability and in fatiguability by long-continued practice and increased tolerance for loud tones respectively.

It should be emphasized that the irregular nature of the data from 990 through 1010 cps. at higher intensities is no chance occurrence. Differences between points varying by no more than two cps. are often of the order of several db. and often show formal statistical significance. Investigation of the output of the earphone with a standard six cc. closed acoustic coupler showed no difference at all in acoustic output through the 20 cps. frequency range. It seems likely that the individual's auditory system varies in an unpredictable way even through rather restricted frequency ranges. This variation may lie anywhere in the system, from the acoustic impedance of the external canal and eardrum to the sensitivity of the hair cells or first-order nerve fibres.

The broad peaks of roughly $\pm$ ten cps. in Figures 1-3 have a curious resemblance to the $\pm$ ten cps. range at 700 cps. through which a single nerve

fibre is maximally sensitive (Galambos and Davis (4). It is, however, difficult to see anything physiologically important in this resemblance, because the acoustic energies in the single fibre study are minimal, while the peaking in fatigue is maximal with relatively high acoustic energies.

The $\pm$ 10 cps. peaking in the fatigue data can hardly have been due to the scattering of energy inevitable in brief tones. In the first place, one should consider primarily the first or stimulating tone in this connection rather than the shorter test tone. It is the effect of the first tone, not the second tone, which is under test. Now this first tone is 435 msec. long, rising and decaying smoothly in 25 msec.; and its repetition rate is so slow it can be disregarded. It seems clear both mathematically and phenomenologically that any side-band frequencies must be so weak and brief as to be negligible. The case of the second tone is not so clear-cut. It was 50 msec. in duration at the half-down point, so that the rise and decay times are an appreciable fraction of the whole. However, since no possible way exists to present brief tones while concentrating energy exclusively to the exact stated frequency, this could not be helped. (In any case, whether frequencies other than the specified frequency were presented in the test tone is in one sense beside the point: If the first tone, which we take to be pure 1000 cps., does not affect adjacent frequencies, then when the test tone is set at these adjacent frequencies one would expect somewhat less fatigue than at 1000 cps. But we find that approximately equal fatigue does occur. Therefore adjacent frequencies <u>are</u> affected by the first tone, and the fatigue pattern is as pictured in Figures 1-3. The only alternative is that when the test tone is tuned to, say 1006 cps., what one is measuring is the 1000 cps. component in the test tone; which seems unlikely in view of the shape of the pattern).

We find in these data another indication of the relatively coarse frequency analysis of which the peripheral organ is capable. The peaking, such as it is, can account for only a portion of the discriminatory powers of the organism, and is not even as marked as the peaks exhibit-

ed by the simultaneous masking experiment, with which the present technique is most closely allied. Perhaps in simultaneous masking the additional possibilities of inhibition, increased summation, et cetera, help to sharpen the gradients. It is evidently the case that some sort of neural lens must refine the diffuseness revealed in the data of Figures 1-3.

The evidence on which we conclude the fatigue pattern to be an expression of events prior to first-order nerve fiber activity rests upon the demonstrations (13) that an ear fatigued in the manner of this paper exhibits recruitment; and that recruitment is definitely a non-neural event centered within the cochlea, if not specifically a hair cell effect (5).

SUMMARY AND CONCLUSIONS

Auditory fatigue was determined in five Os to 1000 cps. tones of 30, 50, 70, and 90 db. sensation level. The spread of fatigue to closely adjacent frequencies was particularly examined. The method of residual fatigue was used to avoid the intrusion of beats in the simultaneous masking experiment. Almost no "peaking" of fatigue effects was observed to the weaker intensities. At higher intensities, a broad maximum effect was found extending to $\pm$ 10 cps.

This peaking is not related to the pitch discrimination ability of the Os; however, the whole range of discriminatory ability was not completely sampled.

These data in general confirm observations to the effect that the peripheral organ presents frequency-wise a relatively coarse pattern which is somehow sharpened and elaborated centrally.

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